

DESIGN FOR PRODUCING FIBERGLASS FABRIC IN A LUNAR ENVIRONMENT

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ABSTRACT

The purpose of this project was to design a method of producing a fabric material on the lunar surface from readily available glass fibers. Various methods for forming fabrics were analyzed to determine which methods were appropriate for the lunar conditions. A non woven process was determined to be the most suitable process for making a fabric material out of fiberglass under these conditions. Various resins were considered for adhering the fibers. A single thermoplastic resin (AURUM) was found to be the only applicable resin. The end product of the process was determined to be suitable for use as a roadway surfacing material, canopy material, reflective material, or packaging material. A cost analysis of the lunar process versus shipping the end-product from the earth suggests that the lunar formation is highly feasible. A design for a lunar, non woven process was determined and included in the following document.

RECOGNITION OF NEED

As a result of increasing interest in lunar exploration, the need for various materials useful in carrying out this process has arisen. Because of extremely expensive transport costs, research has begun to reveal what raw materials available on the lunar surface might be utilized to produce useful exploration materials. One research effort carried out by students at Clemson University entitled, Lunar Fiberglass: Properties and Process Design, proposes processes for producing a fiberglass composite in fiber form from readily available raw materials on the lunar surface. The ability to produce fiberglass fibers on the lunar surface from lunar materials naturally brings about the need to process these fibers into a usable form such as fabric. The need for such a process that utilizes readily available fiberglass fibers to produce products useful in lunar applications eliminates the tremendous costs of transporting such materials from the earth. This need was the focal point of the research done during this project.

PROBLEM STATEMENT

The purpose of this research project was to create a method of producing a fabric on the lunar surface. The fabric had to have a minimum width of half a meter, be composed of readily available fiberglass fibers, and be useful in a number of applications on the lunar surface.

The process to make the fabric was to be operational while fully exposed to the lunar environment. Any beneficial effects of the lunar environment (such as micro-gravity) were to be incorporated into the design.

Because of the limited amount of power available on the moon, a power constraint was established. The maximum power available for the total process had to be no more than five kilowatts.

To make the process economically feasible, a constraint was placed on the use of non-lunar materials. Any earth materials necessary had to be kept to a minimal weight.

Another cost reduction constraint required a minimal amount of monitoring and maintenance by direct human contact. Any direct maintenance by human hands had to occur no more than twice a month.

The final requirement of the process was that the cost of producing a required mass of the end product (in a given amount of time) be less than the cost of shipping the same mass of product from the earth.

LUNAR CONDITIONS

The lunar environment must be considered when designing systems for operation. The first criterion that must be addressed is the lunar atmosphere. The moon's surface has no atmosphere, thus all materials must be able to withstand a hard vacuum. The lack of atmosphere allows meteorites, dust, solar and cosmic radiation to collide with the surface. This calls for materials that will be able to withstand radiation. Dust particles must be cleaned off of all surfaces that are exposed, or the dust must be prevented from contacting those surfaces. Only underground shelters could prevent damage by meteorites, so this effect was not considered in the design. The lack of atmosphere also means that heat can not be carried away by convection. Radiation and conduction are the only means of thermal control. The atmosphere condition

also causes a layer of absorbed gas on a surface of a material to be completely or partially removed. Certain coatings such as silver and gold can prevent this from happening. The removal by evaporation of lubricants, and of the absorbed gas layer which can act as a lubricant, causes an increase in friction which can lead to material damage. However, the removal of the absorbed gas layer may inhibit crack formation.

Another major factor of the lunar environment is that gravity is only one-sixth that of earth. Thus processes that depend on gravity to carry materials from one section to another in manufacturing must be altered to fit this condition. Micro-gravity has an advantage in that ultra pure materials, such as fiberglass fibers, can be made.

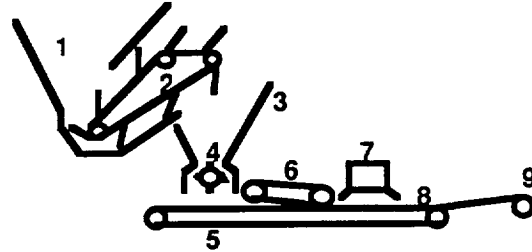
Due to the moon's near total lack of magnetosphere, magnetic control of devices will not function. The solar wind will strike the lunar surface having no magnetic deflection. Materials will need to be designed to be unaffected by the solar wind.

The spin of the moon is such that one side always faces the earth. Because of this, the lunar day is four weeks long, two weeks exposure to the sun and two weeks exposure to space. The temperature extremes go from 250 degrees F to -250 degrees F. Materials that do not substantially alter their properties due to this temperature difference must be used. The moon is seismically quiet compared to the earth, so quake resistance calculations are not needed.

RESIN

The resin used for this project is a super heat resistant thermoplastic polyimide, AURUM, developed by Mitsui Toatsu Chemicals, Inc.. Aurum is chosen because of its thermoplastic properties in addition to the outstanding heat, cold resistance, mechanical/electrical properties which are suitable for use in a variety of applications in the aerospace industry. The resin melt temperature is approximately 390-415 degree Celsius. The glass fibers are assumed to have the resin in powder form already applied to them during the sizing process. This powdered resin acts both as a lubricant and a binder for the glass fibers. Because Aurum is a thermoplastic resin, it does not need to be cured but simply melted. As soon as the resin melts, it will bond to the fibers uniformly throughout the fiber mat to produce a fabric with a strength of 1156 kPa. The resin itself has a strength of approximately 136 kPa. One advantage of this type of polyimide resin is that it does not boil or foam when melted in a vacuum. The final product is 15% resin by weight. After melting, the binder is allowed to cool by radiation and conduction.

SCHEMATIC OF PROCESS



1. Main Bin
2. Paddle Conveyor
3. Secondary Bin
4. Feed Roller
5. Main Conveyor
6. Compression Conveyor
7. Infrared Heating
8. Cooling Area of Main Conveyor
9. Take-up Roll

MACHINE COMPONENTS

Main Bin

Fiber that is to be used in this process is going to be in staple form and thus must be stored in large batches. A large storage container is needed to hold these fibers. This main bin will act as the storage container and provide surge protection for the rest of the system. The fiber will enter the bin from the production process through the large 3 m x 3 m opening in the top and be funneled to a smaller opening of 1.5m x .75m which leads to the paddle conveyor. The fiber will then leave the main bin via the paddle conveyor from the bottom portion of the bin.

The main bin will be made of aluminum due to the metal's low density but relatively high strength. Being that the gravitational force on the moon is roughly 1/6 that of the earth, the bin will not be subjected to high forces. Therefore, The walls of the bin do not have to be very thick and will need little support.

Paddle Conveyor

The paddle conveyor consists of an aluminum frame, aluminum rollers, bearings, and a belt made of a thin sheet of an aluminum-copper alloy with a composition of 96% Al and 4% Cu. The belt is 17 m long, 1.5 m wide and 0.001 m thick and has a series of 5 cm high paddles that are 0.3 m apart which will be used to carry the fibers from the main bin to the secondary bin. This conveyor will have one drive pulley, two non-drive pulleys, and three idlers which will keep the belt at proper operating

tensions. The speed of the conveyor was determined to be 3.09 m/hr (see Appendix A1 for calculations.)

Secondary Bin

The purpose of the secondary bin is to supply the main conveyor belt with the fiberglass via the feed roller. The feed roller is located at the bottom of the secondary bin. The secondary bin is 1.5 meters high, 2 meters wide, and 0.005 meters thick. The bin walls are sloped 28 degrees from the vertical. The mass of the bin is approximately 120 kg.

Feed Roller

The feed roller is the mechanism that insures an even laydown of the fiberglass on the conveyor. Fibers from the secondary bin fall through a 2 m by 0.1 m opening to the feed roller which deposits 70.7 kilograms of sized fiber per hour of operation onto the conveyor. In order to achieve this laydown rate, the roller requires a speed of 7.06 revolutions per hour (see Appendix A2). Small "hooks" are located at certain intervals along the roller and are spaced in such a way as to allow random fiber orientation laydown on the conveyor. This will insure that the fiberglass mat has dimensional stability. The hooks are also slightly bent at the tip in order to grab fibers from the secondary bin if a clog occurs where the fibers enter the roller. There is approximately a 1 mm clearance between the tip of the hook and the secondary bin which provide a space so that fibers caught on the top of the hook will not be crushed between the hook and the bin. The hook spacing and the low gravity will combine to give an even laydown of fibers onto the web.

Main Conveyor

The fabric process chosen requires a main conveyor to effectively transport the fiberglass from the feed roller to the mat formation process. This conveyor picks up the fibers from the feed roll and moves the fibers to the infrared heater positioned down the conveyor. The conveyor is 4.75m long on one side from the center of the end roller to the center of the drive roller. The conveyor material will be 1.05m wide and 10 mm in thickness. The speed of the conveyor will be 8.63 m/hr. Using formulas, values, and assumptions from conveyor literature it was calculated that a 152.4mm roller was necessary to uphold the tension in the belts and required revolutions per minute (see Appendix A5). A 42.75mm shaft was found to be the shaft size that would provide the necessary strength in the system. In fact, the shaft is over designed for its purposes but was needed because of the large face width that is present in the system. A 1/4 hp motor was found to be needed to fulfill the desired speed of the conveyor. In order to achieve the 8.63 m/hr the pulley must rotate at 18 revolutions per hour. In addition to the drive pulleys, idlers must be employed to prevent sag in

the conveyor belt. By calculation, the idlers should be placed 2.0m apart (see Appendix A4). In order to fit the design, idlers will be placed 1.6m apart, which will provide a better tension restoration. The conveyor will be made out of hot butyl material with a coating of silver. The hot butyl stands up well under high temperatures but has problems degrading in a vacuum. To take care of problems in the vacuum, the silver is used to coat the butyl material. Experts on material properties have confirmed that this material design should be adequate. Skirt boards will be placed 78 mm from the edge of the conveyor belt. The skirts are used to keep any material on the belt from falling off. The skirts will only be 50 mm high because of the small width of the product before and after compression.

Compression Conveyor

The compression conveyor is used to compress the fibers into a web of the desired thickness (5 mm). This conveyor moves at the same speed that the main conveyor moves. The compression conveyor has the same material composition as the main conveyor. The conveyor is 500.6 mm long, 1.05 meter wide, and moves at a speed of 18 revolutions per hour. The belt is 10 mm thick and is made of hot butyl coated with silver.

Infrared Heating Lamps

Many of the heating processes used on earth use convection as the primary way of transporting the heat. Large ovens need a medium to carry heat from the heating source to the material being heated. In a vacuum, heating is a much more difficult process than heating on earth because heating by convection is no longer a possibility. Therefore the only ways of heating on the moon is either by conduction or radiation. Radiation doesn't require a medium to transport the heat which makes it a good heating source on the lunar surface. The main factor for heating by radiation is the emissivity of the material that is to absorb the radiation and the intensity of the radiation. Glass has a high emissivity and thus also has a good absorptivity and will be heated very easily by radiation. Given this, the resin will be melted by infrared lamps that will be housed in a metal reflector box with dimensions of 1m long by .25 m wide by .33m high. The housing of the lamp should reflect most of the radiation down to the mat which will improve the efficiency. As the radiation is absorbed by the glass and resin, the temperature will rise up to the melting point of the resin. The entire fabric formation process is going to be operated during the time the equipment is exposed to the sun, which will influence the amount of power required to heat the fabric. During this time of fabric formation, the temperature range on the moon is approximately 50 to 120° C. Therefore the amount of power needed for the curing process will also change as the temperature varies between the 50° and 120° C. Given these two numbers, the final curing

temperature of the process (400°C), the mass rate and the specific heat of the glass, the power required to heat the fabric will range from 4.38 kW to 5.49 kW. When the power of the motors is added to these numbers the total power ranges between 5.31 kW and 6.42 kW. See Appendix A3 for the power calculations.

Take-Up

The method chosen to take up the fabric is the take-up roll which is used in textile manufacturing today. This method is simple and easily implemented. There are problems with this method however. A weeks worth of fiberglass mat production produces a roll that has a mass approaching 12,000 kilograms and a diameter of just over 3 meters. The lunar gravity works to the advantage in regards to mass. Twelve thousand kilograms on the earth would weigh nearly 26,200 pounds. That same mass on the moon weighs only 4,400 pounds, which is still heavy, but more manageable. The diameter of the roll could be greatly reduced if the width of the fabric were increased. However, power considerations prohibit this. Guide bars attached to the sides of the take-up roll keep the mat from spilling over the side. The rollers would only have to be changed 26 times per year based on these calculations.

MECHANICAL ELEMENTS

Parts considered here include pulleys, idlers, shafts, bearings, and motors. On the main conveyor, two pulleys, one driving and the other non-driving need to be installed to move the conveyor belt. Since the loads are so small compared to earth uses, a 152.4mm pulley with a 42.75mm shaft will be able to support the necessary force requirements. As for shafts required to move the pulleys the 42.75mm shaft just mentioned will be sufficient for all moving parts (rollers, pulleys). Again the small shaft can be used because of low forces and speeds. In fact, the shafts will be over designed for the process which will allow for an increase in production rate if desired. Idlers are necessary to keep the belt from sagging in between the pulleys. For the main conveyor, idlers should be placed 1.6m apart on both the upper and lower parts of the conveyor. 50.8mm idlers will be sufficient to keep the conveyor at its proper tension. Bearings will be deep groove single row ball bearings with a 43mm diameter, from the FAG Corporation. Since forces will be so small the smallest and cheapest bearing was chosen that meets the need. The motor chosen to drive the moving elements was a 1/4 hp Leeson Electric variable speed motor. This motor will be able to handle the roller, conveyors and take-up. Five of these motors will be necessary. Gear reductions for each case will be necessary. The motors are still a little oversized which means that rates could be increased and the motors still be able to perform. This is why the motors were chosen to be a little larger than

needed. All parts will be made of aluminum (see Appendices A4, and A5 for calculations).

LUBRICANT

In the design of the fabric process, various pieces of equipment are needed. Many parts rotate and require the use of bearings. In order to keep these parts in good working condition, a suitable lubricant is necessary. Considerations for a proper lubricant was difficult because of the environment that the material would have to perform in. First of all, the lubricant needed to work in a vacuum, which ruled out many possible oils and greases. Secondly, the material needed to withstand the high temperature of the moon without losing its viscosity. Oils and greases, solid lubricants, laminar solids, ceramics, and polymers were explored. After looking at many possibilities, a mix between a grease and solid lubricant was chosen. Shell Apiezon High Vacuum grease and molybdenum disulfide were decided upon. Since most solid lubricants are applied with either a grease or oil, the best characteristics of each material were mixed to form an excellent lubricant. The grease works very well in vacuum situations but has limited temperature effectiveness. The MoS₂ on the other hand has excellent temperature properties but lacks the vacuum ability of the high vacuum grease. It should be noted that both the grease and the MoS₂ have been tested in vacuums at temperature extremes and have performed well. In mixing the two, the properties of the lubricant should become even better. By mixing the two together, the lubrication of the moving parts is fulfilled. From looking at experiments done in a vacuum at high temperatures, the estimated life of the lubricant is six months. This is very good, seeing that only twice a year will the lubricant have to be changed. A sufficient amount should be applied in order to achieve full-film lubrication, which will reduce friction forces and provide better efficiency.

CONTROL SCHEME

In any process design, some control strategy must be formulated. No specifics are given here in regards to equipment since it was not required for this particular part of the design.

At the beginning of the process, weigh cells are necessary on the main bin to keep the fiberglass from filling too high. The control of these weigh cells will return to production of the fiberglass itself, where the regulation will be made. Secondly, a velocity control is necessary on the paddle conveyor to keep the flow into the secondary bin at the proper rate. Readouts will be taken from the weigh cells on the secondary bin and mass monitor on the web laydown conveyor. The readings are

put into the paddle velocity control and the paddle speed is regulated.

As previously mentioned, a weigh cell monitor will be employed to keep track of fiber buildup in the secondary bin. Next, a velocity control will be employed on the feed roller to keep the mat at a constant mass. Readouts from the mass monitors at the web laydown position and final take-up will be fed back to the feed roller velocity control. If mass readings are too high, the roller will slow down, and if too low, the feed roller speeds up.

A mass monitor will be employed on the conveyor to keep the mat at the correct mass. Values will be fed back to the velocity control of the feed roller and conveyor. A velocity monitor will also be supplied on the compression conveyor and connected to the velocity control of the conveyor. This will help to insure that the fiberglass fabric will be not be torn or damaged through the processing points.

Next, a temperature monitor will be used to check the temperature of the formed fabric to insure that the resin is being cured and thus obtain the necessary strength. A velocity control will also be employed on the take-up roll. Values from the mass monitor and velocity monitor will also be fed back to the velocity control of the feed roller to maintain the uniform feed that is necessary.

In general, two controls have been employed on the equipment in order to maintain operations even though one of the monitors may fail. This faulty piece of equipment could then be replaced without having to shut down the process. This is done to alleviate downtime and keep production going.

CONCLUSIONS

A fiberglass fabric can be produced on the lunar surface that is both useful and cost efficient. Nonwoven fabric, while not as strong as a woven fabric, is easier to manufacture and has adequate strength for the intended uses described. The nonwoven process moves slowly and contains a minimum amount of moving parts, thus the design should be extremely reliable. Cost savings over a three year lifespan of the process are in the tens of billions of dollars, compared with shipping the fabric from the earth. Research into more efficient heating methods and resins with lower melting temperatures could drive these cost savings even higher. Overall, production of a fiberglass fabric on the lunar surface is a highly feasible process that merits more research and development.

RECOMMENDATIONS

Due to time constraints, we were not able to thoroughly investigate all aspects of the design. We recommend that the following subjects receive a complete investigation.

First, the heating method did not take into account available solar power. Since the process was designed to

run only during daylight hours, solar heating of the resin should be looked at more closely. A scientist at NASA suggested an induction heating device that would substantially lower power consumption. However, it is not known if this heater would be adequate for our purposes.

Next, the take-up method is bulky and heavy. Perhaps robotically changing the rolls at more frequent intervals could be investigated. Also, there are folding methods used in textiles today that may be applied to the lunar situation.

A complete control system for this process was not done. An outline of where monitors and control hook-ups should be placed was included in the report, but details of this process have not been calculated.

The method of sizing the fiber in pre-processing was not included in the design problem. A Clemson University study suggested one method of accomplishing this, but it was not detailed.

Transport of the fibers from sizing to processing has not been discussed. A possibility for this is a conveyor system similar to the design shown in this report.

A storage method for the take-up roll has not been discussed.

Lunar dust was not thought to be a serious problem for this process. If the dust is found to cause problems, such as weight on the take-up roll, a cover for the process could be designed.

Cooling of the fabric is done by radiation and some conduction. A more efficient conduction cooling method would shorten the length of the conveyor system. A tent structure that shields the fabric from solar radiation would increase the radiation cooling.

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ACKNOWLEDGEMENTS

Mr. Leon Bates. Dexter Aerospace Materials Division. The Dexter Corporation.

Mr. Hugh Berges. Plant Manager. Clark-Schwebel Fiber Glass Corp.

Mr. J.W. Brazell. Department of Mechanical Engineering. Georgia Institute of Technology.

Dr. John Buckley. Nasa Langley Research Center.

Mr. Paul Cavano. Nasa Lewis Research Center

Dr. Prashant Desai. Department of Textile & Fiber Engineering. Georgia Institute of Technology.

Dr. Lewis Dorrity. Department of Textile & Fiber Engineering. Georgia Institute of Technology.

Dr. James Hartley. Department of Mechanical Engineering. Georgia Institute of Technology.

Mr. Lee Hyde. Mitsui Toatsu Chemicals, Inc.

Ms. Carol Jaster. Dow Chemical USA.

Dr. Lieng - Huang Lee. Xerox Webster Research Center.

Dr. Greg Olson. Department of Textile & Fiber Engineering. Georgia Institute of Technology.

Mr. Suneer Patel. Department of Textile & Fiber Engineering. Georgia Institute of Technology.

Dr. Roy Peek. Clark-Schwebel Fiber Glass Corp.

Dr. Terry Sinclair. Nasa Langley Research Center.

Dr. Wayne Tincer. Department of Textile & Fiber Engineering. Georgia Institute of Technology.

Dr. Steve Warner. Department of Textile & Fiber Engineering. Georgia Institute of Technology.

APPENDICES

A1: Paddle Conveyor Speed Calculations

$P = \text{Density} = 1100 \text{ Kg/m}^3$

$V_{\text{trough}} = \text{Volume of trough} = .05\text{m} * 1.5\text{m} * .3\text{m} = .023\text{m}^3$

$P_r = \text{production rate} = 70.7 \text{ Kg/hr}$

$L_t = \text{Distance between troughs} = .11\text{m/trough}$

$S_{\text{conveyor}} = \text{Speed of conveyor (m/hr)}$
 $= P_r / (P * V_{\text{trough}}) * L_t$
 $= 3.09 \text{ m/hr}$

A2: Feed roller calculations

The total volume between the feed roller and the tip of the hook is calculated as follows:

$(1 \text{ meters length}) * (\text{difference between the areas})$

$(1) * (\pi) * (.0089^2 - .0072^2) \text{ meters}^3$

$.00949075 \text{ meters}^3$

The total volume occupied by the hooks can be approximated as follows:

$(.05 \text{ meters length}) * (.019 \text{ meters high}) * (.005 \text{ meters wide})$

$$.00000475 \text{ meters}^3$$

This figure is multiplied by the number of hooks, 80, to give a final volume for the hooks as:

$$.00038 \text{ meters}^3$$

The total volume occupied by the fibers is the difference between these two volumes, and is shown below:

$$.00949075 - .00038$$

$$.00911 \text{ meters}^3$$

This volume is multiplied by the bulk density of the fibers to yield the amount of kilograms of fiber per revolution of the feed roller.

$$(.00911 \text{ meters}^3) * (1100 \text{ kilograms per meter}^3)$$

$$10.02 \text{ kilograms}$$

The total capacity of sized fiber is 70.7 kilograms per hour. This rate is divided by the amount of fiber deposited on the conveyor per revolution of the feed roller.

$$(70.7) / (10.02)$$

$$7.06 \text{ revolutions per hour}$$

A3: Power Consumption Calculations

M_{rate} = Mass rate of Production (Kg/hr)

P = Density (Kg/m³)

V = Speed of production (m/hr)

A = Cross sectional area of Fabric (m²)

q = power

$$M_{\text{rate}} = P * V * A$$

$$M_{\text{rate}} = (1637 \text{ Kg/m}^3) * (8.63 \text{ m/hr}) * (1 \text{ m}) * (0.005 \text{ m}) \\ = 70.64 \text{ Kg/hr}$$

$$C_{p\text{glass}} = \text{Specific heat of glass} = 800 \text{ J/(Kg} * ^\circ\text{K)}$$

$$\text{At } T_{\text{moon}} = 50 ^\circ\text{C} :$$

$$q = M_{\text{rate}} C_p (T_f - T_i) \\ = (70.64 \text{ Kg/hr}) * (800 \text{ J/(Kg} * ^\circ\text{K)}) * (400 ^\circ\text{C} - 50 ^\circ\text{C}) \\ * 1 ^\circ\text{K}/^\circ\text{C} * (^w/\text{J/sec}) * (\text{hr}/3600 \text{ sec})$$

$$= 5490 \text{ W} \\ = 5.490 \text{ kW}$$

$$\text{At } T_{\text{moon}} = 121 ^\circ\text{C} : q = 4.379 \text{ kW}$$

$$q_{\text{range}} : 4.379 - 5.490 \text{ kW}$$

$$q_{\text{infrared lamps}} : 4.38 \text{ KW to } 5.49 \text{ KW}$$

$$q_{\text{total}} = q_{\text{infrared lamps}} + q_{\text{motors}} = 5.31 \text{ KW} - 6.42 \text{ KW}$$

A4: Idler Calculations

Calculation to find spacing of idlers.

$$\text{Sag} = (W * S_i^2) / 8T \quad \text{where } W = \text{weight (Wb + Wm)}$$

S_i = idler spacing

T = tension in belts

Sag taken to be 3% of idler spacing

New equation becomes

$$S_i = 0.24 * T/W$$

$$S_i = 0.24 * 392 / 14.49 = 6.5 \text{ ft}$$

Spacing should be 6.5 ft = 2.0m

For length of conveyor of 32.73 ft (10m), two idlers will be required to maintain tension

A5: Pulley Sizing

Refer to charts that follow. The forces that are obtained are much less than those in the charts. Thus the sizing of these pulleys will more than sufficient.

Face width is approximately 44" = 1.1m

Weight is 60 lbs = 27.3 kg

Diameter is 6" = 152.4mm

Shaft size is 42.75mm

The sizing for the drive pulley and the non-driving pulley will be the same

A6: Cost Comparison

Fabric Formation on the Lunar Surface

Resin Cost:

$$309,000 \text{ Kg of fabric/year} * .15 \text{ Kg resin/Kg fabric} \\ = 46,350 \text{ Kg resin/year} \\ = 102,000 \text{ lb. resin/year}$$

$$102,000 \text{ lb. resin/year} * \$85,000/\text{lb.} \\ = \$8,670,000,000/\text{year for the resin that} \\ \text{must be shipped}$$

Equipment Cost:**Total Weight of Equipment:**

$$\text{Kg} = 4189\text{lb.} \times \$85,000/\text{lb} \\ = \$356,000,000$$

Total Cost for one Year:

$$\$356,000,000 + \$8,670,000,000 = \\ \$9,026,000,000$$

Total Cost for two Years:

$$\$356,000,000 + (2 \times \$8,670,000,000) \\ \$17,696,000,000$$

Total Cost for three Years:

$$\$356,000,000 + (3 \times \$8,670,000,000) \\ = \$26,366,000,000$$

Shipment of Preformed Fabric

23,700 Kg fabric/lunar rev.

x 13 rev./year

x 2.2 lb./Kg x \$85,000/lb.

= \$57,692,000,000/year

= \$57.7 Billion/Year

B1: Weights of Machinery and Equipment

Main Bin and Supports	396 Kg
Paddle Conveyor and Supports	665 Kg
Secondary Bin and Supports	201 Kg
Main Conveyor	285 Kg
Compression Conveyor	51 Kg
Infrared Lamps	23 Kg
Take-up Equipment	55 Kg
Motors and Parts-	51 Kg
Control Equipment	45 Kg
Misc.	<u>130 Kg</u>
Total	900 Kg